A SPREADSHEET-BASED TECHNIQUE (LOTUS 1-2-3) FOR SEPARATING TROPICAL FOREST STORM HYDROGRAPHS USING HEWLETT AND HIBBERT'S SLOPE

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ABSTRACT

The inclined line separation technique of Hewlett and Hibbert has been widely adopted to separate delayed flow from the total stream storm runoff. Presented here is the application of the technique to highly responsive storm hydrographs using a personal computer method based on a Lotus 1-2-3 spreadsheet. Using discharge measurements (in $m^3 s^{-1}$), catchment area (in km^2) and time (in Julian days), the separation slope is adjusted on the monitor screen until the precise time at which the end of quickflow as storm runoff gives way to delayed flow may be established. The application of the inclined line method is compared with other separation techniques applied to the same dataset. The annual stream quickflow runoff for the study catchment was calculated by the four different separating lines – (i) best-fit curve, (ii) N-day after peak, (iii) inclined line and (iv) horizontal line – was 250, 312, 368, and 588 mm, amounting to 33, 31, 51 and 78 per cent respectively of the annual total stream runoff. Separation of flow by computer spreadsheet methods may be consistently applied throughout a dataset and therefore have a comparative advantage over more arbitrary techniques. © 1997 John Wiley & Sons, Ltd.

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INTRODUCTION

Hydrographs are considered as a hydrological 'black box' where hydrological process information is stored (Shaw, 1988). A typical storm hydrograph consists of at least delayed flow and quickflow components. Standard analysis of the hydrograph by separating these two components is essential in order to study the runoff characteristics of a catchment in more detail. The shape of the hydrograph and hence the characteristics of the response can be described, for example, by using an index of the 'quickflow component'. Separation of flow components is also required for the construction of a unit hydrograph. Unit hydrographs or unit graphs are considered to be good devices for demonstrating the hydrological characteristics of individual basins (Linsley *et al*., 1975; Shaw, 1988). However, when creating the unit graphs, rainfall duration, time–intensity patterns and areal distribution of rainfall must be taken into account (Linsley *et al*., 1975; Raudkivi, 1979).

Many authors conclude that separation techniques are arbitrary processes (e.g. Linsley *et al*., 1975; Raudkivi, 1979; Richards, 1982). The choice of separation technique is largely dependent on personal preferences, as long as the technique is applied consistently (Bates and Davies, 1988) and acceptable separation methods may be achieved by using either a physical–graphical or chemical approach. Some techniques are just simple graphical procedures (Wilson, 1974; Linsley *et al*., 1975; Raudkivi, 1979) while some are mathematically complex (e.g. Britles, 1978; Hino and Hasebe, 1986). The inclined line separation technique was developed for small forested catchments in humid regions (Hewlett and Hibbert, 1967). An inclined line is used to connect the beginning point of the surface runoff with a point on the recession limb of the hydrograph where normal baseflow resumes. It is a refinement of a simple graphical engineering technique, the straight line

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Table I. Example of runoff data in the Lotus 1-2-3 spreadsheet, for calculating and separating storm runoff (see also Table IV)

A	A	B	C	D	E	F
1	**Time**	**Point**	**Regression**	**Regression**	**Block**	**Total**
2		**Q**	**Q**	**Q**	**Q**	**Quickflow**
3			**(EQ. 2)**			
4			**Y= 0.0131 x X**	**adjusted slope**		
5						
6						
7	312.005	0.03502	4.08727	0.03502		
8	312.567	0.03169	4.09463	0.03169		
9	312.577	0.03592	4.09476	0.03182		
10	312.601	0.04732	4.09507	0.03214		
11	312.604	0.09748	4.09511	0.03217		
12	312.610	0.23199	4.09519	0.03225		
13	312.615	0.47361	4.09526	0.03232		
14	312.620	0.86864	4.09532	0.03238		
15	312.624	1.32191	4.09537	0.03244		
16	312.625	1.30255	4.09539	0.03245		
17	312.631	1.21510	4.09547	0.03253		
18	312.646	0.97909	4.09566	0.03272		
19	312.658	0.83021	4.09582	0.03288		
20	312.672	0.58524	4.09600	0.03307		
21	312.677	0.51292	4.09607	0.03313		
22	312.679	0.48919	4.09609	0.03316		
23	312.683	0.47720	4.09615	0.03321		
24	312.693	0.44164	4.09628	0.03334		
25	312.738	0.30919	4.09687	0.03393		
26	312.846	0.18389	4.09828	0.03534		
27	313.000	0.12539	4.10030	0.03736		
28	313.008	0.12268	4.10040	0.03747		
29	313.362	0.07562	4.10504	0.04210		
30	313.544	0.06848	4.10743	0.04449		
31	314.000	0.05276	4.11340	0.05046		
32	314.295	0.04418	4.11726	0.05433		

method, which draws a horizontal line from the point at which the runoff begins, to the point of intersection with the recession limb. However, the technique is more suitable for use with ephemeral streams (Chow *et al*., 1988).

The inclined line technique separates ‘quickflow’ and ‘baseflow’ along a separation line with a rate of increment of 0·0131 m^1 s^{-1} km^{-2} for each day (Hewlett and Hibbert, 1967). This value gave a relatively short time-base to single peaked hydrographs in their study area and permitted large storms separated by a period of about three days to be calculated as separate events. The same value has, however, been used in entirely different regions (cf. Walling ((1971) in Ward and Robinson (1990)).

THE STUDY AREA

The hydrographs analysed in this study are from a 1·7 km^2 undisturbed lowland tropical rainforest catchment referred to as W8S5. The area in Sabah, East Malaysia, is set in undulating country of the geologically heterogeneous melange unit of the Kuamut Formation, where siltstone, sandstones, chert, spillites and tuffs contain many easily eroded lithologies, producing shallow soils or layers of unconsolidated rock (*c*.1–2 m). The drainage density of the catchment is approximately 20 km km^{-2}. At 4°N of the equator the area experiences only the edge effects of the seasonal monsoons with an average annual rainfall of 2725 mm (1988 to 1993). Saturated hydraulic conductivity (K_s) in the soils examined ranged from 186 to 305 mm h^{-1} at 0–12 cm depth, in excess of the maximum 30 min storm rainfall intensities of 100 mm h^{-1}, down to 64 mm h^{-1} at 12–24 cm (Bidin *et al*., 1993). The catchments typically produced distinct hydrographs of less than 24 h duration.

THE SPREADSHEET ANALYSIS

1. A basic familiarity with spreadsheet techniques and organization is required. For this analysis the values used were discharge (in m^3 s^{-1}), catchment area (in km^2) and time (in Julian days). The slope value of 0·0131 is

Table II. The data spreadsheet with a blank line inserted for the intercept point between the separation line and the falling limb of the hydrograph (line 32)

	A	B	C	D	E	F
29	313.362	0.07562	4.10504	0.04210		
30	313.544	0.06848	4.10743	0.04449		
31	314.000	0.05276	4.11340	0.05046		
32						
33	314.295	0.04418	4.11726	0.05433		

not adjusted as discharge values are per square kilometer; however, if values have not been converted then the slope is multiplied by catchment area (km^2). In this example the spreadsheet has been organized in such a way that time occupies column A and instantaneous discharge column B, although, as with any spreadsheet, the data may be ordered and restructured to the users' convenience.

2. Convert the line into a linear regression relationship between y (discharge; Table I column B) and x (time; Table I column A). The units used here are as given above. Let:

$$y = mx + c \tag{1}$$

where y = point discharge on the slope line, x = time when y is calculated, m = Hewlett and Hibbert's slope, and c = point on y where the regression is intercepted (initially the value is arbitrary).

But c is a constant, therefore:

$$\begin{aligned} y &= mx \\ y &= 0{\cdot}0131x \end{aligned} \tag{2}$$

3. Put the values of y (Equation 2) into column C of the data processing spreadsheet (column C in Table I).

(a) Adjust the regression values (column C) so that the line will intercept exactly at the threshold of the rising stage of the storm hydrograph (column D). Note that in this example the intersection occurs on row eight where the actual point discharge (column B) and regression value after adjustment (column D) are equal i.e. D8=C8–(C8−B8). This is the start of the rising stage and it should be noted that the rest of the values in column D are equal to the column C values minus the constant value derived from this point, i.e. (C8−B8)=4·06294. For example, D9=C9−4·06294.

(b) Plot the hydrograph temporarily on the screen with the actual stream discharge and the adjusted slope regression values, e.g.
  x−axis range: A7 ... A32
  first data range: B7 ... B32
  second data range: D7 ... D32

(c) View the hydrograph and zoom into the area where the separation slope intercepts with the falling limb of the hydrograph. This can be done by adjusting the x−axis and data ranges, e.g.
  x−axis range: A31 ... A32
  first data range: B31 ... B32
  second data range: D31 ... D32
  View the graph and identify as accurately as possible the time where the hydrograph intercepts the separation line; for this example it is 314·055.

(d) On the spreadsheet, insert one line between the two data points, line 31 and 32, that bracket this value. Line 32 now becomes line 33 and 32 (now a blank line) is the intercept point (Table II). Type the intercept time derived from 3 (c) in column A, line 27. Calculate the discharge for the intercept (for measured and slope curves) using the integration formula (Table III), e.g.

  for actual value at B32: [(A32–A31)*B33+(A33–A32)*B31]/(A33–A31)
  for slope regression D32: [(A32–A31)*D33+(A33–A32)*D31]/(A33–A31)

(e) View the graph one more time without altering the graph settings. If the integrated values do not exactly fall on the intercept point, slightly adjust the time (A32) until they do so, i.e. when B32 and D32 values are equal at four decimal places (see line 32, Table III).

Table III. The data spreadsheet when the data points for the intercept point between separation line and the hydrograph falling limb are integrated

	A	B	C	D	E	F
29	313.362	0.07562	4.10504	0.04210	3032.56224	
30	313.544	0.06848	4.10743	0.04449	1132.97184	
31	314.000	0.05276	4.11340	0.05046	2388.33101	
32	314.055	0.05116	4.11412	0.05118	246.91473	
33	314.295	0.04418	4.11726	0.05433	988.48863	

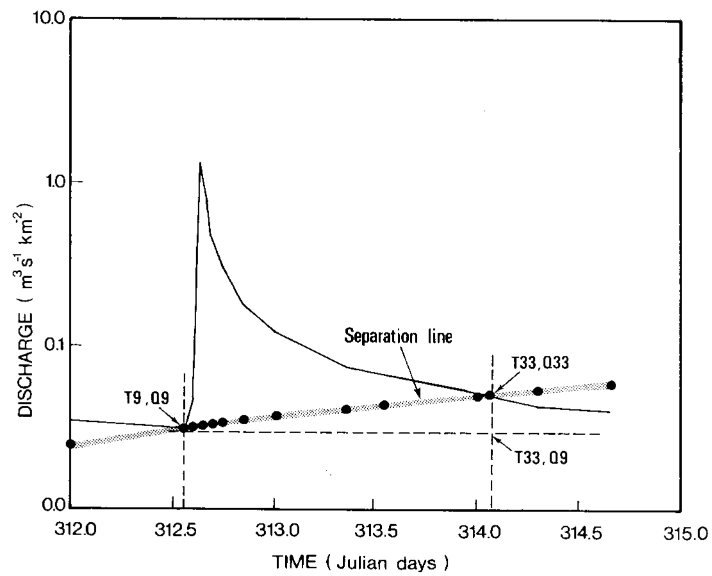

Figure 1. Schematic procedure for calculating quickflow by using a line separation technique, i.e. Hewlett and Hibbert's slope. The example shown is from the W8S5 stream, Sabah, Malaysia, November 1991.
Quickflow (m^3) = (Total Q between $T9$ and $T33$) − [$864000(T33–T9)(Q9+1/2(Q33–Q9))$]
where T = time, Q = discharge

4. To calculate the total discharge between each element of the hydrograph, using Pythagoras' theorem, type the formula for 'Q block' in column E (Table IV). Total quickflow can now be calculated (Figure 1, Tables III and IV).

COMPARISON OF RESULTS

For the W8S5 catchment water year July 1991 to June 1992, the modified inclined line separation technique described here was compared with three other hydrograph separation techniques: (i) 'best-fit' curve method (Ward, 1975); (ii) specific N-day after peak discharge (Linsley *et al*., 1975); and (iii) horizontal line (Ward, 1975). Spreadsheets were also created to apply the separation lines (ii) and (iii). The best-fit curve point, however, was determined using a 'French Ruler', with many choices of curves, to fit the falling limb of the individual hydrographs.

The results for the four separation techniques differed greatly ($P < 0{\cdot}001$). The horizontal line gave the highest quickflow volumes, followed by the inclined line method, N-days after peak and the line determined by best-fit curve (Table V). The annual quickflow runoff depth for the W8S5 basin was 250, 312, 368 and 588 mm, as calculated by the four different separating lines (best-fit curve, N-day after peak, inclined line and horizontal line), amounting to 33, 41, 51 and 78 per cent respectively of the annual total stream runoff.

Table IV. Spreadsheet details (e.g. Lotus 1-2-3) for calculating and separating the storm hydrograph

A	A	B	C	D	E	F
1	**Time**	**Point**	**Regression**	**Regression**	**Block**	**Total**
2		**Q**	**Q**	**Q**	**Q**	**Quickflow**
3						
4	**Julian day**	**m3 s-1 km2**	**m3 s-1 km2**	**m3 s-1 km2**	**m3**	**m3**
5						
6						
7			**(i)**	**(ii)**	**(iii)**	**(iv)**
8						
9						
10						
11	(i) Regression value for Hewlett and Hibbert's separation slope, y = mx					
12	i.e 0.0131 x time. eg 0.0131*A8					
13						
14	(ii) Values of column C after correction: Achieved by adjusting the values so that the					
15	separation line intercepts the start of the rising stage of the storm hydrograph (see					
16	Table 1, line 8).					
17						
18	(iii) Total discharge between each point of the hydrograph.					
19	86400*(A8-A7)*(B7+1/2*(B8-B7)) eg. formula at line 8 column E.					
20	i.e. calculating total discharge between line 7 and line 8.					
21						
22	(iv) Total quickflow determined by Hewlett and Hibbert's separation line.					
23	@Sum(E9..E33)-(86400*(A33-A9)*(B9+1/2*(B33-B29))					
24						

Table V. Monthly variation in quickflow volumes (*Qq*) and quickflow : total stream runoff coefficients (*q/Qt*%) for the W8S5 catchment

Month, year	Rainfall (mm)	Best-fit		N-day after peak		Inclined line		Horizontal line	
		Qq (mm)	*q/Qt*%	*Qq* (mm)	*q/Qt*%	*Qq* (mm)	*q/Qt*%	*Qq* (mm)	*q/Qt*%
Jul 91	131·5	4·5	27·1	7·1	42·8	6·2	37·3	10·5	63·3
Aug 91	248·6	16·4	50·3	20·4	62·6	25·8	79·1	32·5	99·7
Sep 91	115·4	4·8	30·2	7·9	49·7	8·6	4·1	13·8	86·8
Oct 91	373·3	86·2	57·5	96·1	64·1	140·8	93·9	149·5	99·7
Nov 91	372·7	77·2	35·2	96·6	44·1	103·9	47·4	182·0	83·1
Dec 91	211·2	20·5	12·8	30·3	18·9	28·2	17·6	74·9	46·8
Jan 92	106·0	3·7	7·8	6·1	12·9	6·5	13·7	20·7	43·8
Feb 92	108·0	3·9	16·3	5·8	24·3	8·2	34·3	14·4	60·3
Mar 92	69·0	3·4	77·3	3·9	88·6	4·2	95·5	4·3	97·7
Apr 92	30·0	0·9	47·4	1·5	78·9	1·8	94·7	1·9	98·9
May 92	190·0	9·5	59·7	10·8	67·9	14·8	93·1	15·9	100·0
Jun 92	316·0	19·0	28·3	25·0	37·2	36·5	54·3	67·2	100·0
Annual	2271·7	250·0	33·1	311·5	41·3	385·5	51·1	587·6	77·9

DISCUSSION

For the perennial W8S5 stream hydrographs, each separation technique had its limitations. The horizontal line method was generally not suitable for use when separating the hydrograph during a wet period following a dry period as the ground water storage is increased and therefore the baseflow level during such a period is elevated. To negate variable baseflow levels, a horizontal line was determined for each individual month after the first storm hydrograph of the month. The line could extend into the following month until the next hydrograph occurred.

The other three separation techniques are applicable under any weather condition. Nevertheless, the best-fit curve method was found to be more dependent on individual operator judgement and did not give consistent results.

The N-day after peak technique could be applied consistently as it is derived from an equation with a fixed time variable. However, underestimation of the quickflow component would be expected for large hydrographs

Table VI. Quickflow : total stream runoff coefficients (*Qq/Qt*%) for selected tropical rainforest catchments

Catchment (size)	*Qq/Qt*%	Separation technique	Source
Queensland, Australia ($0·26\,km^2$)	47	Unknown	Bonnell and Gilmour (1978)
Dominica ($1·22\,km^2$)	10–20	Best fit	Walsh (1980)
Kalimondo, Java, Indonesia ($0·19\,km^2$)	5–7	Chemical tracer (Si)	Bruijnzeel (1982)
W8S5, Sabah, Malaysia ($1·7\,km^2$)	41	(i) N-day after peak	This study
	51	(ii) Inclined line	
	46	Average of (i) and (ii)	

produced by large rainfall events. On the other hand, for small hydrographs the quickflow component is expected to be overestimated. However, an examination of the results over longer time periods would produce reasonably representative values as big storm events occur only a few times each year, whereas small storm events occur very often but individually only produce small volumes of quickflow.

The inclined line method as presented here can be employed accurately and gave consistent results; however, whether or not the slope is suitable for the W8S5 catchment is unknown. The N-day after peak and inclined line separating techniques were believed to be more reliable. Both techniques gave consistent results and are easily applied using simple computer spreadsheets. In this example, as the N-day after peak and inclined line separation techniques were both considered reliable for the W8S5 stream hydrographs, the value for the quickflow stream runoff coefficient for W8S5 was produced by averaging the results of the two techniques. This gave an annual average of 46·2 per cent for the study period. This value is similar to the figure of 47 per cent quoted for rainforest in Queensland (Bonell and Gilmour, 1978). The quickflow proportions for both sites are high when compared to the values quoted for other tropical rainforest regions (Table VI). Bonell and Gilmour (1978) consider that their catchment is responsive due to the extremely high rainfall intensities and low subsoil permeabilities.

The high volumes of quickflow and rapid channel response observed in the W8S5 catchment can be attributed to combination of the catchment characteristics and high rainfall intensities, producing subsurface exfiltration in a catchment with high drainage densities (Bidin, 1995).

CONCLUSION

A variety of methods are currently available for hydrograph separation and, depending on needs, each provides a useful tool for quantifying channel runoff in process-based hydrological investigations. However, given the sensitivity of the techniques, comparisons of quickflow runoff data can only be made using similar, clearly described techniques. The modified inclined line separation technique adapted for a computer spreadsheet has value in that it may be applied consistently to small catchment storm hydrographs. For the highly responsive W8S5 catchment the results compare favourably with other separation techniques.

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